LETTER

A Method for Gathering Sensor Data for Fish-Farm Monitoring Considering the Transmission-Range Volume*

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SUMMARY We have proposed a fish-farm monitoring system. In our system, the transmission range of acoustic waves from sensors attached to the undersides of the fish is not omnidirectional because of obstruction from the bodies of the fish. In addition, energy-efficient control is highly important in our system to avoid the need to replace the batteries. In this letter, we propose a data-gathering method for fish-farm monitoring without the use of control packets so that energy-efficient control is possible. Instead, our method uses the transmission-range volume as calculated from the location of the sensor node to determine the timing of packet transmission. Through simulation evaluations, we show that the data-gathering performance of our proposed method is better than that of comparative methods.

key words: *fish farm, undersea sensor networks, monitoring, acoustic data communication*

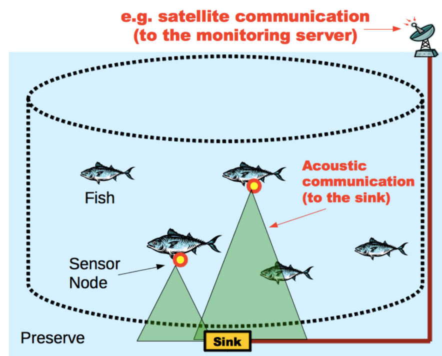

Fig. 1 Fish-farm monitoring system.

1. Introduction

In recent years, sensor network technologies have attracted the attention of primary industries such as agriculture, livestock, and aquaculture. Our research group has previously proposed a novel system as shown in Fig. 1 for monitoring fish farms to improve their efficiency [1], [2]. In our proposed monitoring system, a sensor node is attached to the undersides of all or some fish in the farm to monitor the health status of the entire fish stock. We assume that the costs of installing our system and of the sensor nodes themselves are low compared with the value of the farmed fish. Fish-mountable sensor nodes have been developed generally in the area of bio-logging research for monitoring wild animals, to the extent that some off-the-shelf products are now available. However, those types of sensor node usually do not allow communication among multiple nodes. In contrast, the data obtained by each fish-mounted sensor node in our system are transmitted to a sink node. Once collected, the sink node transmits the assembled monitoring data to the monitoring server via a satellite or mobile network.

Because the durations involved in fish farming can be long (e.g., farming tuna takes about three years), our system requires each sensor to gather data in an energy-efficient manner. In addition, obstruction by the body of the fish to which a sensor is attached means that the transmission of acoustic waves is not omnidirectional in our system, thereby affecting the performance of acoustic data communication. In this environment, the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) mechanism that is widely used in wireless network systems cannot work correctly because of collisions among hidden nodes. To avoid this hidden-node problem, the Request To Send/Clear To Send (RTS/CTS) handshaking mechanism is generally used [3]. However, in RTS/CTS handshaking, a number of control packets are transmitted and received among nodes, but that process would consume too much energy in the present context. Some researchers have proposed data-gathering mechanisms for underwater sensor networks [4]–[6]. In [2], we also proposed a simple data-gathering method for a fish-farm monitoring environment. Again, however, all those mechanisms require control packets for their operation, which means that the sensor nodes would consume too much energy while transmitting, receiving, or overhearing such packets.

In this letter, we propose a data-gathering method for a fish-farm monitoring environment without the use of control packets. In our proposed method, there is no requirement for an individual sensor node to send or receive control packets. Therefore, the energy consumption is lower compared with that in conventional mechanisms, albeit at the expense of the data-gathering performance. In our proposed method, the transmission-range volume (TRV) is used instead to control the transmission timing of the packets. In this letter, we eval-

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uate our proposed method through simulation experiments using the ns-3 discrete-event network simulator [7].

2. Fish-Farm Monitoring System

2.1 Fish-Farm Model

In this letter, we assume the same fish-farm model as in [2]. There are N sensor nodes n_i $(1 \leq i \leq N)$ in a domain below which a sink node is located. The shape of domain is a cylinder whose radius of R and depth of L. The location of sensor node n_i is described as (r_i, ϕ_i, z_i) in a cylindrical coordinate system whose origin is the top center of the domain. We assume that a sensor node is attached to the body of a fish, and that its transmission range is conical with apex angle θ to the vertical.

2.2 Relationship between Transmission-Range Volume and Packet Collisions

In this environment, packets sent by sensor nodes to the sink node using CSMA/CA may be lost because of hidden nodes. In Fig. 1, two sensor nodes each send a packet to the sink simultaneously because they are unaware of each other. Consequently, the sink node receives neither packet because of collision.

We investigate the relationship between packet collisions and the TRV of sensor nodes through simulation experiments using the ns-3 simulator [7]. Here, the transmission range is the sensor node's conical region of transmission in the domain, and is determined by the shape of the domain and the location of the sensor node. In the simulation experiments, each sensor node transmits its packet with random timing in a period. We note here that we use the comparative method 3 with the same simulation settings described in Sect. 4.1 in this simulation.

Figure 2 shows the cumulative distribution function (CDF) of the TRV of a sensor node that causes collisions. As shown in Fig. 2, when the TRV of the sensor node is large, the gradient of the graph is high, which indicates a high probability of packet collision. The reason for this is as follows. Sensor nodes located in the upper part of the domain have a large transmission range. However, the probability that they are within the transmission range of other sensor nodes is low, making it difficult to detect packet transmissions from those other nodes. Therefore, packets from sensor nodes with a large transmission range are easily lost because of collisions when packets are sent with random timing. Thus, to reduce collisions, sensor nodes should send packets in order of their TRVs. In the next section, we propose a data-gathering method considering the TRV.

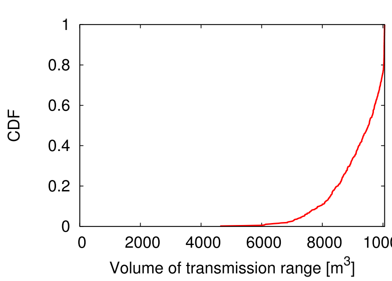


Fig. 2 Cumulative distribution function of the transmission-range volume of sensor nodes with collisions.

3. Proposed Method

3.1 Assumption

In our proposed method, data are gathered from all sensor nodes to the sink node periodically at interval T. We assume that the start timing of this cycle is synchronized among the sensor nodes, which can be accomplished using traditional time-synchronization methods. Alternatively, a sensor node generally has a clock with which to record events, and that could be used instead; because our method assumes that the interval T is sufficiently large compared to the clock error, precise synchronization is not required. The details of the time synchronization are beyond the scope of this letter.

In addition, we assume that each sensor node knows its current location (r_i, ϕ_i, z_i), the shape of the domain, and the vertical angle θ of the conical transmission range. Therefore, sensor node n_i can calculate its TRV v_i based on its current location. For example, sensor data such as acceleration or water depth, which are often measured in wild-animal monitoring in bio-logging research, could be used to estimate the current location of a sensor node. The details of this localization in a fish-farm environment are beyond the scope of this letter, but we will address them in future work.

Here, we remark on the receiver module of our sensor nodes. Unlike in previous research, the sensor nodes in our proposed method do not require full receiver modules to receive control packets or data. Rather, they require only a module for carrier sense to determine whether the channel is in use. As such, our proposed method is able to decrease the development cost and energy consumption of the sensor nodes.

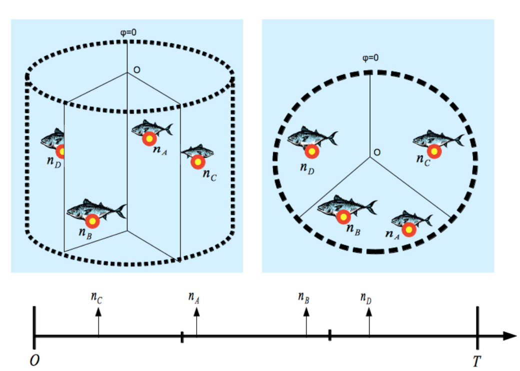
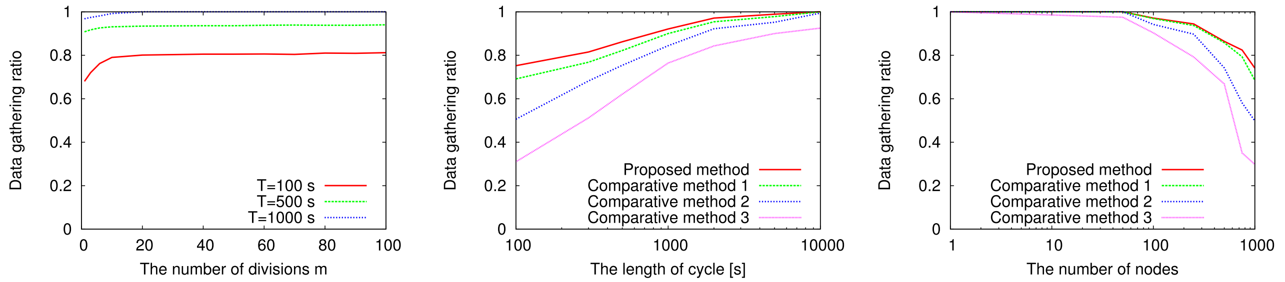
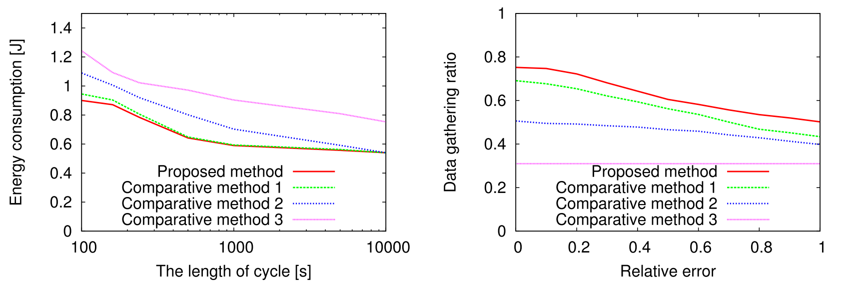


Fig. 3 Example of sensor-node location and timing of packet transmission.



(a) Data-gathering ratio versus number of divisions.
(b) Data-gathering ratio versus cycle length ($N = 1000$).
(c) Data-gathering ratio versus number of nodes ($T = 100$)



(d) Energy consumption versus cycle length
(e) Data-gathering ratio versus relative error of current location ($N = 1000$, $T = 100$)

Fig. 4 Simulation results

3.2 Behavior of Sensor Nodes

In our proposed method, sensor node n_i determines its transmission time t_i by using the following equation at the start of a cycle:

$$t_i = \left(\frac{1}{m}\left\lfloor m\frac{\phi_i}{2\pi}\right\rfloor + \frac{1}{m}\frac{V_{\max} - v_i}{V_{\max}}\right)T, \tag{1}$$

where $V_{\max}$ is the maximum TRV of the sensor node and m is a parameter that determines the number of divisions of the domain.

After determining the transmission time t_i at the start of a cycle, sensor node n_i enters sleep mode. When transmission time t_i arrives, sensor node n_i enters active mode and sends its data packet to the sink node using CSMA/CA. Then, it returns to sleep mode until the start of the next cycle.

Figure 3 shows schematic overhead and vertical views of sensor nodes and an example of the timing of packet transmission. In this example, we use $m = 3$ and divide the domain into three regions.

4. Evaluation

4.1 Evaluation Environment

We use the network simulator ns-3 [7] with the Underwater Acoustic Network (UAN) module for the simulation experiments. In the simulation, the domain is a cylinder whose radius is $R = 15$ m and depth is $L = 20$ m, values that come from domains in our university. The sink node is located 10 m under the center of the base of the domain, in which we place $N = 1000$ sensor nodes randomly. We use the random waypoint mobility model [8] to model fish mobility, for which the maximum velocity is set to 3 m/s, the minimum velocity is set to 1 m/s, and the stop time is set to zero. The length of each data packet is set to 10 bytes, the data rate is set to 1000 bps, and the vertical angle θ of the transmission range is set to $2\pi/3$ rad. For the communication modules, the packet-transmission power is set to 500 mW and the carrier-sense power is set to 100 mW.

In the evaluation, we measure the data-gathering ratio and the communication-module energy consumption per node. The former is the ratio of the number of packets received at the sink node to the number of sensor nodes.

For comparison, we also conducted simulation experiments using three comparative methods. In *comparative method 1*, the following function is used instead of Eq. (1):

$$t_i = \left(\frac{1}{m}\left\lfloor m\frac{\phi_i}{2\pi}\right\rfloor + \frac{1}{m}\frac{z_i}{L}\right)T. \tag{2}$$

In this method, the node coordinates (r_i, ϕ_i, z_i) are used to determine the packet-transmission timing instead of calculating the TRV. In *comparative method 2*, we use

$$t_i = T(V_{\max} - v_i)/V_{\max}. \tag{3}$$

In this method, the TRV alone is used to determine the transmission timing. *Comparative method 3* is the simplest method, in which the time t_i is chosen randomly between zero and T, making the packet-transmission timing random regardless of the node location. In the following, all results are averaged over 500 measurement results.

4.2 Evaluation Results

We begin by plotting in Fig. 4 (a) the data-gathering ratio against the number of divisions m. As shown, the data-gathering ratio of the proposed method converges to steady values for $m > 10$. Therefore, we set $m = 10$ in the following evaluation.

Figures 4 (b) and 4 (c) show the data-gathering ratio plotted against cycle length and number of nodes, respectively. As shown, the data-gathering ratio of the proposed method is highest compared with the other methods. When we compare the proposed method and comparative method 1, the data-gathering ratio of our proposed method is higher. Therefore, the TRV is effective for determining the timing of packet transmission. In comparative method 2, the data-gathering performance is degraded by collisions among sensor nodes that are symmetric about the z-axis because they have similar TRVs and packet-transmission timings. In comparative method 3, the packet-transmission timing is random and the data-gathering performance is the lowest.

Figure 4 (d) shows energy consumption plotted against cycle length. As shown, the energy consumption in our proposed method is the lowest compared with the other methods. In our proposed method, sensor nodes transmit their data packets in order of their TRVs, and so at the time of packet transmission by a sensor node, there is a lower probability that the node is within the transmission range of any other node. Therefore, the number of carrier-sense decreases, thereby lowering the power consumption.

Finally, we evaluate the effect of accuracy of current location information on the performance of data-gathering. In this evaluation, we use following location $(\hat{r}_i, \hat{\phi}_i, \hat{z}_i)$ as the current location.

$$(\hat{r}_i, \hat{\phi}_i, \hat{z}_i)^{\mathrm{T}} = (1 + u(\epsilon))(r_i, \phi_i, z_i)^{\mathrm{T}}, \tag{4}$$

where ϵ is a relative error and $u(\epsilon)$ is a function to obtain random value between $-\epsilon$ and ϵ. Figure 4 (e) shows data-gathering ratio plotted against relative error ϵ. As shown, the data gathering ratio decreases according to relative error. However, the data gathering ratio of our proposed method is highest. In addition, the performance is much higher than that of comparative method 3 which does not use location information. Therefore, we can conclude that use of TRV is efficient even if there is certain error in location information.

5. Conclusion

In this letter, we proposed a data-gathering method for fish-farm monitoring without the use of control packets. In our proposed method, the transmission-range volume is used instead to determine the timing of packet transmission. Through simulation experiments, we showed that the data-gathering ratio of our proposed method is higher than those of comparative methods, while the energy consumption is lower.

As future research, we intend to evaluate our method under more-realistic situations. In addition, we plan to extend our proposed method to handle multiple sinks as a way to improve the data-gathering ratio.

Acknowledgments

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